Calhoun
Institutional Archive of the Naval Postgraduate School

Calhoun: The NPS Institutional Archive

DSpace Repository

Theses and Dissertations 1. Thesis and Dissertation Collection, all items

1950

A comparison of the jet augmentation resulting from steady and pulsating primary flow.

Stone, Ried W.

University of Minnesota

http://hdl.handle.net/10945/24626

Downloaded from NPS Archive: Calhoun

DUDLEY KNOX LIBRARY

Calhoun is the Naval Postgraduate School's public access digital repository for research materials and institutional publications created by the NPS community. Calhoun is named for Professor of Mathematics Guy K. Calhoun, NPS's first appointed -- and published -- scholarly author.

Dudley Knox Library / Naval Postgraduate School
411 Dyer Road / 1 University Circle
Monterey, California USA 93943

http://www.nps.edu/library

Thesis
S76

Thesis
S76

Library
U. S. Naval Postgraduate School
Annapolis, Md.

DUDLEY KNOX LIBRARY
NAVAL POSTGRADUATE SCHOOL
MONTEREY, CALIFORNIA 93943-5002

A COMPARISON OF THE JET AUGMENTATION RESULTING FROM STEADY AND PULSATING PRIMARY FLOW

A Thesis
Submitted to the Graduate Faculty
of the
University of Minnesota

by

Ried W. Stone

In Partial Fulfillment of the Requirements
for the
Degree of Master of Science
in
Aeronautical Engineering

August 1950

PREFACE

Extensive work has been done with the principal of the air ejector. This device consists of a duct through which a high velocity jet is discharged. Secondary air is drawn from a region of low pressure, mixes with the high velocity jet in the duct and is discharged to a region of higher pressure. An ejector will operate with no pressure rise or with a pressure drop, and still increase the net thrust of the installation.

In the field of aviation, this type of device has been used for cooling as well as for increasing the thrust output. However, the published work done in this field to date appears to be restricted to that of steady flow. It is the purpose of this report to compare the thrust augmentation obtained with steady flow with that obtained with pulsating flow.

SUMMARY

This report presents the results of an investigation comparing the thrust augmentation obtained by discharging a high velocity jet of steady flow air into an air ejector with that obtained by discharging a pulsating jet of air into that same ejector. The pulsating device was designed to operate close to the resonant frequency of the augmentor.

The basis used to compare results between the steady flow case and the pulsating flow case was the pressure ratio of p_o/p_c, where p_o was atmospheric pressure and p_o the compressed air pressure. In the latter case, however, the pressure ratio was only an average one, for the column of mercury used to measure the pressure ratio would only indicate the average pressure and not the varying pressure. This was also true in measuring the thrust in the case of the pulsating flow, for here again, the galvanometer would read only the average thrust. Thus, while the support for the model was vibrating under the pulsing thrust, the galvanometer held steadily on an average reading.

The results of the test indicate that greater thrust was obtained without the augmentor than was obtained with the augmentor. This is known to be in error, and may be caused by flow separation

and skin friction through the augmentor. It is believed that with minor adjustments to the equipment, the expected thrust augmentation would be obtained with the augmentor. It is difficult to say what effect these changes would have on the results of the test.

Results obtained for the thrust of the augmentor and jet together indicate a slightly greater amount of thrust in the case of the pulsating flow.

The thrust acting on the augmentor alone was appreciable in the case of the pulsating flow, but amounted to zero for the steady flow test.

It is recommended that if further work along these lines is done, that a variable speed motor be used to drive the pulsating device. This would enable making the tests at the exact resonant frequency of the model, as well as permitting a study of the effect of the pulsating frequency upon the thrust.

It should also be of interest to design a support for the model such that the amplitude of the thrust variations in the pulsating case could be recorded and studied.

INTRODUCTION

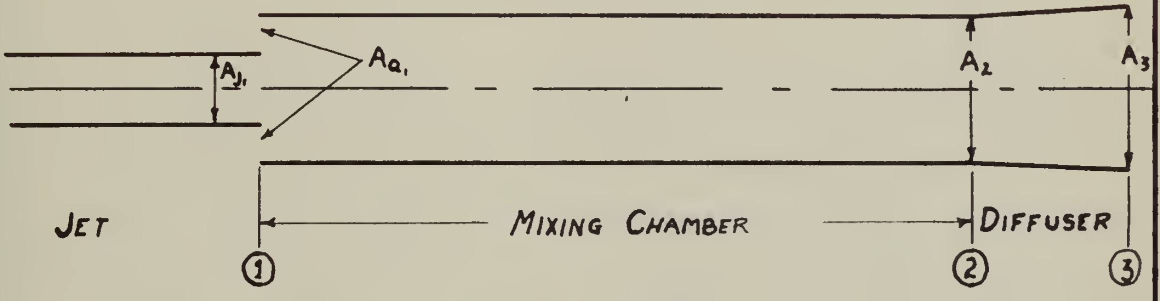
It has long been known that the overall efficiency of jet propulsion engines can be increased by the use of an augmentor in which the mass flow is increased and the exit velocity decreased. The air ejector is such a device.

Since very little has been published on pulsating flow, accepted steady flow theory was used to design an air ejector for maximum thrust augmentation, and this ejector used with both steady flow and pulsating flow to compare results.

The theoretical analysis neglects frictional losses and assumes mixing to be complete. The mixing chamber is designed for constant area. Compressibility is taken care of by the use of the thermodynamic General Energy relation, and the equations of Continuity, Momentum and State were all used in the development.

Thrust measurements were made in two ways. First, by measuring the total thrust of the jet and augmentor, and secondly, by measuring the thrust of the augmentor alone.

NOTATIONS



W = Weight of air flow, #/sec.

V = Velocity, ft/sec.

p = Absolute pressure, #/ft.^{2}

T = Absolute temperature, ° Rankin

R = Universal gas constant = 53.3

C_p = Specific heat at constant pressure = .24

J = Joule's equivalent = 778 ft. #/B.T.U.

g = Acceleration of gravity = 32.2 ft/sec/sec

r = Air flow ratio = W_a/W_j

F = Thrust in pounds

A = Area in ft.^{2}

Subscripts

o = Free stream conditions

1,2,&3 = Stations 1, 2, & 3 respectively

a = Secondary (air)

j = Primary (jet air)

c = Compressor (temperature and velocity)

EQUIPMENT AND PROCEDURE

The air ejector, or augmentor, used in this experiment was designed theoretically for optimum thrust augmentation. To determine the optimum nozzle area of the augmentor, a plot of thrust augmentation against area ratio was made. The basic formulas for these calculations are developed in the Appendix. These basic equations are:

$$F_{aug} = \left[\frac{(W_a + W_j)V_3 - W_jV_j}{W_jV_j} \right] 100 \tag{21}$$

$$W_{a_1} = \frac{P_o}{RT_o} \left(\frac{P_1}{P_o}\right)^{\frac{1}{\gamma}} \sqrt{2gJC_pT_o \left[1 - \left(\frac{P_1}{P_o}\right)^{\frac{\gamma-1}{\gamma}}\right]} A_{a_1} \tag{5}$$

$$W_{j_1} = \frac{P_o}{RT_o} \left(\frac{P_1}{P_o}\right)^{\frac{1}{\gamma}} \sqrt{2gJC_pT_o \left[1 - \left(\frac{P_1}{P_o}\right)^{\frac{\gamma-1}{\gamma}}\right]} A_{j_1} \tag{4}$$

$$V_3 = \sqrt{V_2^2 + 2gJC_pT_2 \left[1 - \left(\frac{P_o}{P_1}\right)^{\frac{\gamma-1}{\gamma}}\right]} \tag{20}$$

$$V_2 = B = \frac{r\, V_{a_1} + V_{j_1}}{1 + r} \tag*{(18a) and (19a)}$$

$$V_{a_1} = \sqrt{2gJC_pT_o \left[1 - \left(\frac{P_1}{P_o}\right)^{\frac{\gamma-1}{\gamma}}\right]} \tag{6}$$

$$V_{j_1} = \sqrt{2gJC_pT_o \left[1 - \left(\frac{P_1}{P_c}\right)^{\frac{\gamma-1}{\gamma}}\right]} \tag{1}$$

$$T_2 = T_{2s} - \frac{B^2}{gR}\left(\frac{\gamma-1}{2\gamma}\right) \tag{18}$$

$$T_{2s} = \frac{r\, T_{as} + T_{js}}{r + 1} = \frac{T_o(1 + r)}{1 + r} = T_o$$

$$r = W_a/W_j$$

$$\frac{A_2}{A_3} = \frac{V_3\, p_o}{V_2\, p_1}\left(\frac{p_1}{p_o}\right)^{\frac{\gamma-1}{\gamma}} \qquad (24)$$

By assuming values for the pressure ratio (p_1/p_o), it was possible to solve first for the thrust augmentation and then for the area ratio (A_2/A_3) necessary to give the assumed pressure ratio. In order to avoid blocking of the mass flow through the jet, which occurs at the critical pressure ratio, it was necessary for (p_o/p_c) (p_1/p_o) $\geq$ 0.528. Having selected the value of (p_o/p_c) equal to 1/1.5 or 0.667, (p_1/p_o) was limited to values between 0.7925 and 1.0000.

Results of the above calculations are found in Tables I and II and are plotted in Figures 1 and 2. From the plot of thrust augmentation against area ratio, an area ratio of 0.75 was selected. Although this value of 16.77% was not quite the maximum thrust augmentation possible, it was within the limitations of the allowable pressure ratio and resulted in a considerably lower resonant frequency of the ejector, and this latter consideration was important in designing the pulsator.

Having selected the diameters of the mixing chamber and jet such as to give a ratio of secondary air (W_a) to primary air (W_j) of 2.5, using a mixing chamber length equal to five (5)

diameters in accordance with Reference (e), and limiting the angle of expansion in the diffuser to three (3) degrees, the complete design of the ejector followed. (See Figure 3) The augmentor was constructed of brass and the jet of copper.

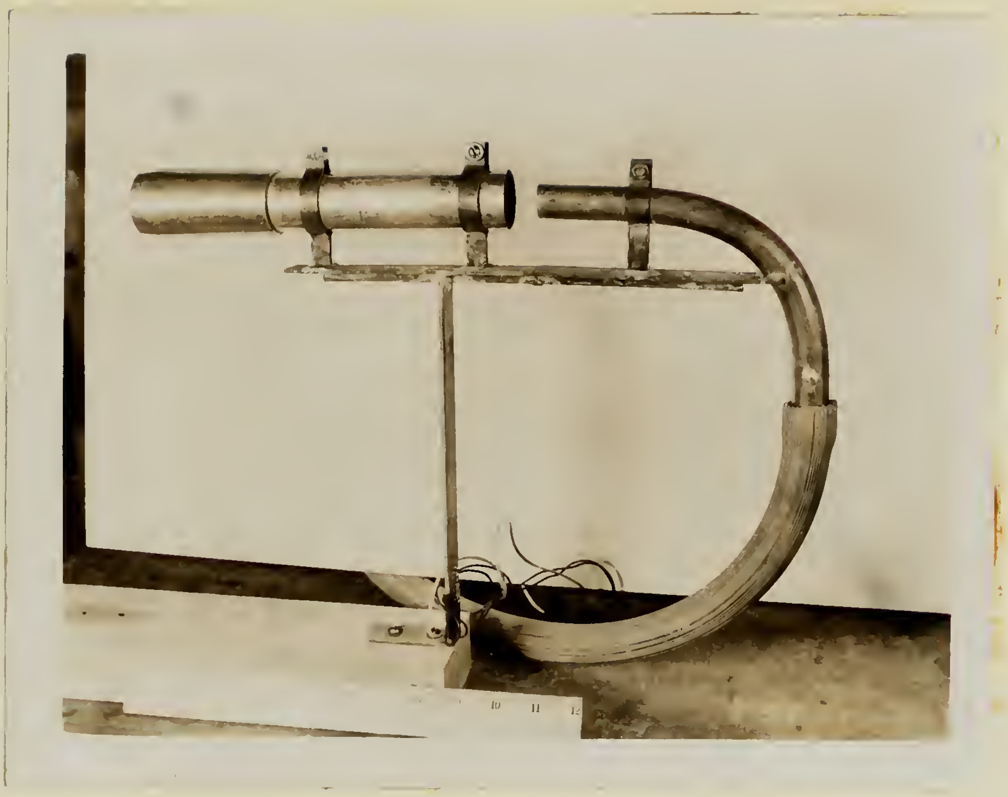
The augmentor and jet were mounted on a support with the jet exit centrally located just at the entrance to the augmentor. Test results of Reference (f) show that the efficiency of the augmentor is seriously effected by placing the jet off center due to reduced secondary air flow and poor mixing. A flexible rubber hose connected the jet to the compressed air source to minimize any thrust tare due to the coupling. To measure the thrust of the augmentor alone, the jet was mounted rigidly and the augmentor left on the support and free to move.

The thrust was read by calibrating the deflection of the model with known loads applied parallel to the centerline of the jet and ejector. The deflection was read by means of two (2) strain gages mounted on the base of the support and connected to a bridge and galvanometer.

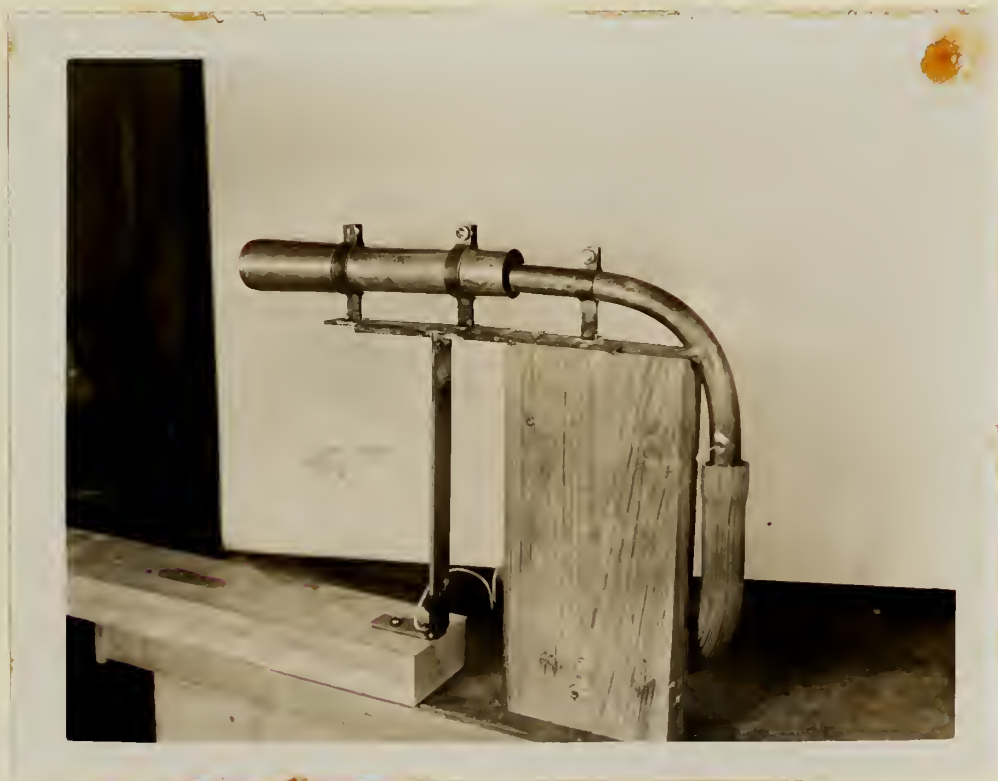
To convert the steady flow source of compressed air to a pulsating source, a pulsating device was designed as shown in Figure 6. This device was inserted between the jet and the compressed air source, and the thrust obtained as for the steady flow

case. To obtain optimum thrust under these conditions, the frequency of the pulsations was made equal to the resonant frequency of the augmentor. This frequency, and the design of the device to obtain it, is solved in the Appendix. However, since the exact calculation of the resonant frequency of a complex shaped device is quite involved, only the general equation for a cylinder was used. This solution gave a frequency of 566 cycles per second or 3396 rpm of the disc creating the pulsations. By using a variable speed motor, it would be possible to adjust the rpm to obtain exact resonant frequency. This was attempted, but a sufficiently powerful variable speed motor was not available and it was necessary to use a constant speed 1/4 horsepower motor.

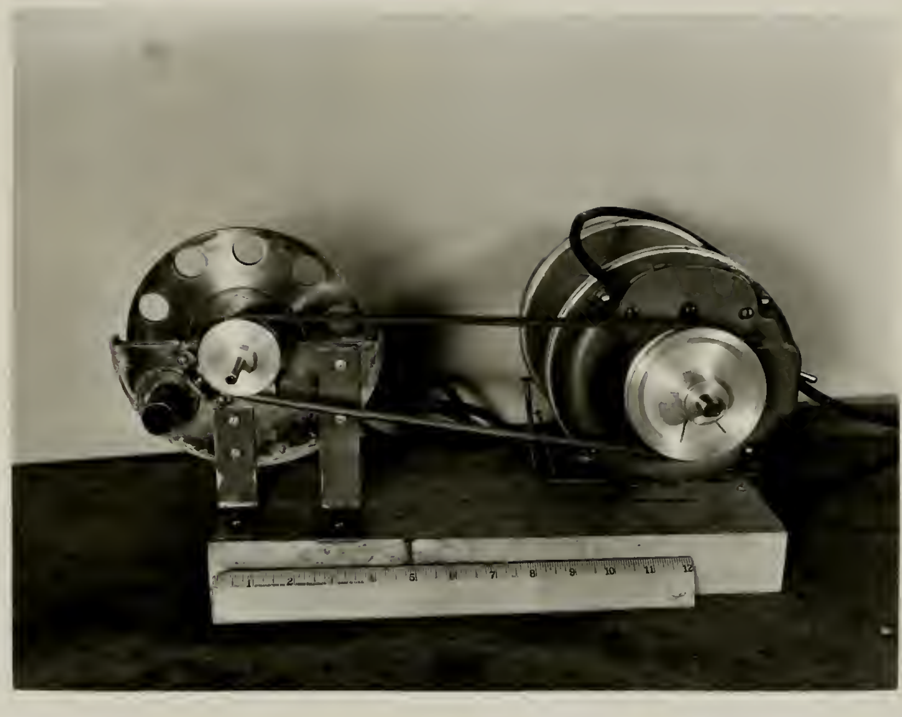
The test was conducted at the University of Minnesota Rosemount Research Laboratory. The air supply was drawn from the hypersonic blow down wind tunnel pressure tank. A total pressure pick-up and a static pressure tap located on the jet were used to adjust the air supply line valve for the desired pressure ratio of p_o/p_o. An average pressure ratio was used in the pulsating case, and this was the basis for the comparison of results.



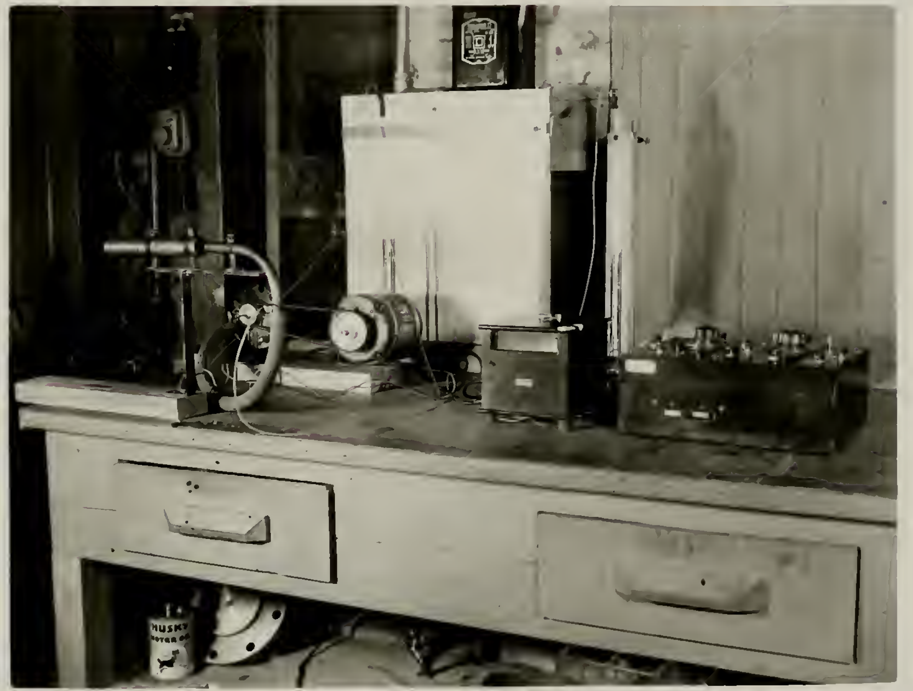
Model Mounted for Total Thrust



Model Mounted for Thrust on Augmenter Alone



Pulsating Device



Test Set-Up

RESULTS AND DISCUSSION

The results of the thrust obtained for various pressure ratios is found in tabulated form in Table V and in graphical form in Figure 5.

The curves of Figure 5 indicate that the thrust acting on the augmentor and jet together was equal to or slightly greater in the case of the pulsating flow. The curves indicate further that more thrust was obtained by removing the augmentor and testing the jet alone, but here again, the pulsating flow gave the greater thrust.

The theoretical development of the augmentor indicated an expected 16.75% thrust augmentation resulting from the use of the augmentor. It is known that the augmentor should increase the thrust. Considering its effect on the jet alone, for a given p_o/p_c, the fact that it reduced the exhaust pressure of the jet will both increase the jet velocity and the mass flow of the jet, and thus increase the thrust of the jet alone, since the thrust is a function of the mass flow and the velocity. Considering the effect of the augmentor on the overall efficiency, by increasing the mass flow through the augmentor and by decreasing the exit velocity, this should further increase the thrust augmentation

obtainable with the use of the augmentor.

The fact that the test results did not show this may be attributable to flow separation at the entrance to the augmentor or through the diffusor section, or it may be caused by skin friction or poor mixing within the augmentor. The walls of the diffuser expand at a three (3) degree angle and should not of itself cause flow separation. Misalignment of the jet with the augmentor may have caused some of this trouble. It is believed that small adjustments of the equipment would result in increased thrust with the augmentor over that of the jet alone.

The curve of Figure 5 also shows that the thrust acting on the augmentor alone was appreciable in the case of pulsating flow, but that no thrust or drag was obtained with steady flow. These results are consistent with those indicating greater total thrust in the pulsating case than for steady flow, but are not consistant with the earlier results showing greater thrust for the jet alone. It may be that the alignment of the jet and augmentor is more nearly correct in this test. Certainly, these results indicate that the augmentor itself is actually increasing the thrust with pulsating flow, and at least is not causing a drag force with steady flow. In line with the earlier discussion, since the thrust of the jet alone is increased by the effect of the augmentor decreasing the exit pressure, the addition of the forces acting on

the augmentor alone should result in greater total thrust in both cases.

Unexpected difficulties involved in constructing the pulsator, and getting it to run at constant speed under the air loadings prevented further testing of the equipment at present. Any further investigation should involve the following consideration:

First, the redesign of the pulsator. This should include milling the disc housing from solid stock and the use of roller bearings. These steps would eliminate the problems involved in the present pulsator discussed in the Appendix.

Second, additional testing of the model. It is known that the positioning of the jet in respect to the augmentor must be such that the jet is located just at the entrance of the augmentor and centered on it. Furthermore, the two must be properly aligned in order to get the proper performance. Before making any more tests, this alignment should be carefully checked.

A pressure survey of the exhaust area would indicate whether there was any flow separation in the diffuser causing a loss in performance.

It would be a simple matter to install static pressure taps at station 1 and 2 in the augmentor permitting an analysis

of the system.

Similar models have been successfully tested with steady flow air, and it is firmly believed that this model, with a few adjustments, will produce the expected performance.

CONCLUSIONS

Although these tests results are not conclusive, they indicate that:

(1) Greater total augmentation was obtained with pulsating flow than with steady flow.

(2) No force acted on the augmentor alone in the steady flow case, but the thrust was appreciable with pulsating flow.

(3) It may be more advantageous to use augmentors on pulsating flow power plants than on steady flow engines.

BIBLIOGRAPHY

Ref. (a) "Tests on Thrust Augmentors for Jet Propulsion", Jacobs and Showmaker, NACA TN 431, September 1932.

Ref. (b) "Jet Propulsion with Special Reference to Thrust Augmentation", Schubauer, G. B., NACA TN 442, January 1933.

Ref. (c) "Design of Nozzles for Individual Cylinder Exhaust Jet Propulsion Systems", Pinkel, Turner and Voss, NACA ACR April 1941, E83.

Ref. (d) "Simple Air Ejector", Keenana and Neumann, Journal of Applied Mechanics v9n2, June 1942.

Ref. (e) "Design of Jet Pumps", Flugel, NACA TM 982, July 1941.

Ref. (f) "A Theoretical and Experimental Investigation of Jet Augmentation", J. G. Wilder, Jr., Curtiss-Wright Corp. Report #BC-357-A-1, September 1945.

Ref. (g) "Theory of Ejectors", H. G. Elrod, Jr., Journal of Applied Mechanics v12n3, September 1945.

Ref. (h) "Tests of Exhaust Propulsion Nozzles", Paul J. Campbell, NACA ARR 3E21, May 1943, W43.

Ref. (i) "Aircraft Ejector Performance", Journal Inst Aero Sci v13n11, November 1946.

Ref. (j) "General Treatment of Compressible Flow in Ejectors and Example of its Application to Problem of Effect of Ejector Addition on Thrust of Jet Propulsion Units", H. H. Ellerbrock, Jr., NACA RM L6L23 1947.

Ref. (k) Hausmann, Erich and Slack, E. P., "Physics", D. Van Nostrand Co., Inc., New York.

TABLE I SOLUTION OF EQUATIONS FOR V_{a_1}, W_{a_1}, V_{j_1} AND W_{j_1}

①	②	③	④	⑤ = V_{a_1}	⑥	⑦ = W_{a_1}	⑧	⑨	⑩	⑪ = V_{j_1}	⑫	⑬ = W_{j_1}
P_1/P_0	$\left(\frac{P_1}{P_c}\right)^{.286}$	[1-②]	KT_0 × ③	$\sqrt{④}$	$\left(\frac{P_1}{P_0}\right)^{.714}$	C_1 × ⑤ × ⑥	② × $\left(\frac{P_0}{P_c}\right)^{.286}$	[1-⑧]	KT_c × ⑨	$\sqrt{⑩}$	⑥ × $\left(\frac{P_0}{P_c}\right)^{.714}$	C_2 × ⑪ × ⑫
1.000	1.0000	0.0000	00000	0	1.0000	0	0.8908	0.1092	682 000	826	0.749	0.2280
0.950	.9854	.0146	91100	302	.9640	.1778	.8775	.1225	764 500	875	.722	.2328
0.900	.9704	.0296	184800	430	.9275	.2450	.8650	.1350	842 500	918	.695	.2350
0.850	.9546	.0454	283000	533	.8907	.2920	.8510	.1490	930000	964	.667	.2370
0.825	.9465	.0535	334000	578	.8718	.3095	.8440	.1560	974 000	986	.653	.2370
0.810	.9415	.0585	365000	604	.8600	.3192	.8390	.1610	1004000	1003	.645	.2380
0.800	.9381	.0619	387000	622	.8525	.3256	.8350	.1650	1030000	1016	.638	.2388
0.7925	.9358	.0642	400500	633	.8466	.3295	.8340	.1660	1036000	1018	.634	.2375
0.750	.9210	.0790	493000	702	.8140	.3510	.8210	.1790	1118000	1058	.610	.2375
0.700	.9030	.0970	605500	778	.7750	.3710	.8040	.1960	1223000	1108	.580	.2365
0.600	.8640	.1360	849000	921	.6940	.393	.7700	.2300	1435 000	1199	.520	.2293

$\frac{P_0}{P_c} = 1/1.5 = 0.667$ $R = 53.3$ $\gamma = 1.4$ $g = 32.2$ $K = 2gJC_p = 12030$ $P_0 = 2116$

$T_0 = T_c = 518.4°R$ $C_p = 0.24$ $J = 778$ $\omega = \frac{A_{a_1}}{A_{j_1}} = 2.5$ $C_1 = \frac{P_0}{RT_0} A_{a_1} = 0.000614$ $P_c = 3172$

TABLE II SOLUTION OF EQUATIONS FOR V_3, A_2/A_3, AND F_{aug}

⑭ = r	⑮	⑯ = V_2	⑰	⑱ = T_2	⑲	⑳	㉑	㉒	㉓ = V_3	㉔	㉕ = $\frac{A_2}{A_3}$	㉖ = F_{aug}	P_2/P_0
⑦/⑬	1 + ⑭	$\frac{⑭⑤ + ⑪}{⑤}$	$\frac{⑯ \times M3}{gR}$	T_0 - ⑰	$\left(\frac{P_0}{P_1}\right)^{.286}$	[1 - ⑲]	K × ⑱ × ⑳	⑰ × $\frac{gR}{.M3}$ + ㉑	$\sqrt{㉒}$	㉓/⑯	㉔② $\frac{P_0}{P_1}$	F	P_1/P_0
0	1.000	826	56.7	461.7	1.000	0	0	682000	826	1.000	1.000	0	1.00
.768	1.768	626	32.6	485.8	1.0196	-0.0196	- 85400	306600	554	.885	.918	11.90	.95
1.042	2.042	668	37.1	481.3	1.0308	-0.0308	- 175300	267700	518	.775	.835	15.05	.90
1.233	2.233	727	44.0	474.4	1.0477	-0.0477	- 272 000	257 000	507	.698	.783	17.30	.85
1.306	2.306	755	47.4	471.0	1.0565	-0.0565	-320 000	250 000	500	.662	.760	16.90	.825
1.341	2.341	774	49.8	468.6	1.0620	-0.0620	-349200	249 800	499	.645	.750	16.77	.81
1.363	2.363	787	51.6	466.8	1.0658	-0.0658	- 370 000	249 000	498	.633	.742	15.89	.80
1.388	2.388	793	52.3	466.1	1.0688	-0.0688	- 386 000	243 000	493	.622	.735	15.93	.7925
1.479	2.479	845	59.3	459.1	1.0856	-0.0856	- 473 000	241 000	491	.581	.714	15.08	.75
1.568	2.568	907	68.3	450.1	1.1075	-0.1075	- 581500	240500	490.5	.541	.697	13.75	.70
1.715	2.715	1022	86.5	431.9	1.1577	-0.1577	-819000	223000	473	.462	.665	7.28	.60

$C_2 = \frac{P_c}{RT_c} A_{j_1} = 0.000368$

$A_{a_1} = 0.00801$

$A_{j_1} = 0.00321$

$F = \frac{[⑦ + ⑬]㉓ - ⑬ \times ⑪}{⑬ \times ⑪}$

$r = W_{a_1}/W_{j_1}$

TABLE III

CALIBRATION DATA

COMPLETE MODEL		AUGMENTOR ALONE	
LOAD	DEFLECT	DEFLECT	LOAD
1 lb.	.50	.03	.005 lb.
2	1.07	.05	.007
3	1.70	.07	.010
4	2.27	.10	.020
5	2.91	.13	.030
6	3.60	.18	.040
7	—	.20	.050
8	—	26	.060
9	—	.30	.070
10	—	.34	.080
		.39	.090
		.42	.100

TABLE IV TEST DATA

	AUGMENTED				JET ALONE				TOTAL PRESSURE					THRUST-Total		THRUST-Jet		
	L	R	ΔP_s	P_s	L	R	ΔP_s	P_s	L	R	ΔP_c	P_c	P_c/P_0	GAGE	POUNDS	GAGE	POUNDS	RPM
STEADY	-.60	-.60	-1.20	28.0	+.20	+.30	+0.50	29.70	8.3	8.3	16.6	45.8	1.568	2.35	4.00	2.40	4.10	
	-.65	-.40	-1.05	28.15	.15	.20	0.35	29.55	7.3	7.3	14.6	43.8	1.500	2.30	3.93	2.35	4.00	
	-.50	-.40	-0.90	28.30	.10	.20	0.30	29.50	6.3	6.3	12.6	41.8	1.430	2.00	3.43	2.10	3.60	
	-.50	-.40	-0.40	28.30	.05	.15	0.25	29.45	5.2	5.2	10.4	39.6	1.355	1.55	2.72	1.62	2.83	
	-.45	-.40	-0.85	28.35	.05	.10	0.15	29.35	4.2	4.2	8.4	37.6	1.287	1.20	2.15	1.30	2.30	
PULSATING	—	—	—	—	—	—	—	—	9.0	9.0	18.0	47.2	1.615	2.60	4.40	—	—	—
	+.35	+.40	+0.75	29.95	+1.30	+1.45	+2.75	31.95	8.2	8.2	16.4	45.6	1.560	2.45	4.15	2.50	4.25	1690
	-.20	-.25	-0.45	28.75	1.10	1.30	2.40	31.60	7.3	7.3	14.6	43.8	1.500	2.30	3.93	2.40	4.07	1690
	-.10	-.10	-0.20	29.00	0.05	0.90	1.95	31.15	6.3	6.3	12.6	41.8	1.430	2.00	3.43	2.20	3.75	1690
	-.25	-.20	-0.45	28.75	0.60	0.70	1.30	30.50	5.2	5.2	10.4	39.6	1.355	1.70	3.00	1.80	3.10	1690
	-.50	-.50	-1.00	28.00	0.40	0.50	0.90	30.10	4.2	4.2	8.4	37.6	1.287	1.35	2.40	1.55	2.72	1690

THRUST ON AUGMENTOR ALONE

	AUGMENTED				JET ALONE				TOTAL PRESSURE					THRUST-Total		THRUST-Jet		
	L	R	ΔP_s	P_s	L	R	ΔP_s	P_s	L	R	ΔP_c	P_c	P_c/P_0	GAGE	POUNDS	GAGE	POUNDS	RPM
PULSATING	+.60	+.70	+1.30	30.5					7.8	7.8	15.6	44.8	1.535	.25	.0580			1695
	0.00	0.00	0.00	29.2					6.2	6.2	12.4	41.6	1.425	.20	.0457			1695
	-.40	-.40	-.80	28.4					5.2	5.2	10.4	39.6	1.355	.18	.0400			1695
	-.60	-.50	-1.10	28.1					4.3	4.3	8.6	37.8	1.295	.15	.0335			1695
	-.60	-.50	-1.10	28.1					3.0	3.0	6.0	35.2	1.205	.05	.0085			1695
STEADY	-.70	-.45	-1.05	28.15					8.2	8.2	16.4	45.6	1.560	0	0			
	-.75	-.60	-1.30	27.90					7.4	7.4	14.8	44.0	1.505	0	0			
	-.75	-.65	-1.40	27.80					6.2	6.2	12.4	41.6	1.425	0	0			
	-.70	-.65	-1.40	27.80					5.2	5.2	10.4	39.6	1.355	0	0			
	-.70	-.60	-1.30	27.90					4.1	4.1	8.2	37.4	1.280	0	0			
	-.60	-.50	-1.10	28.10					3.2	3.2	6.4	35.6	1.219	0	0			
	-.45	-.30	-0.75	28.45					2.1	2.1	4.2	33.4	1.145	0	0			
	-.25	-.15	-0.40	28.80					1.2	1.2	2.4	31.6	1.082	0	0			

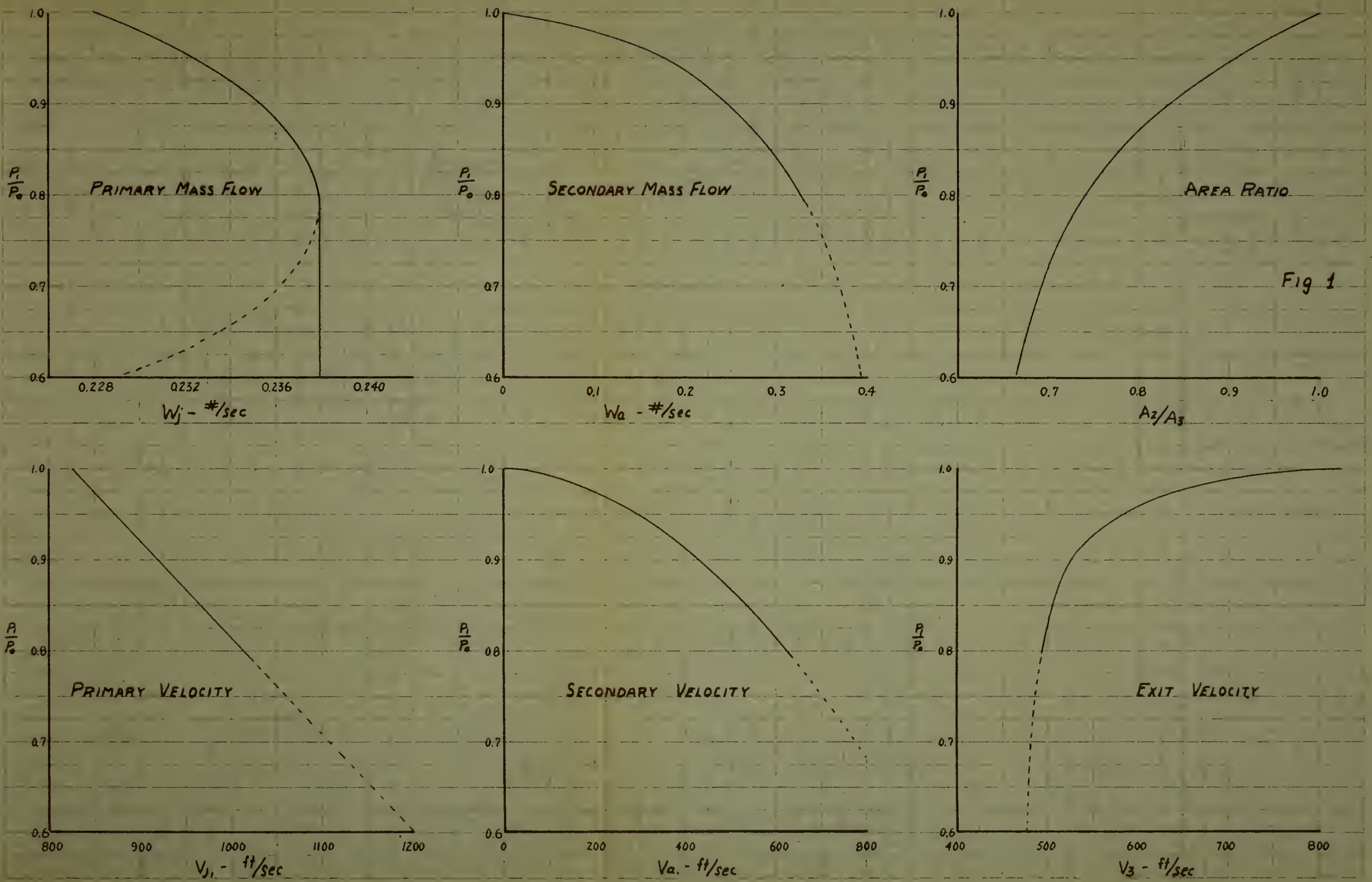
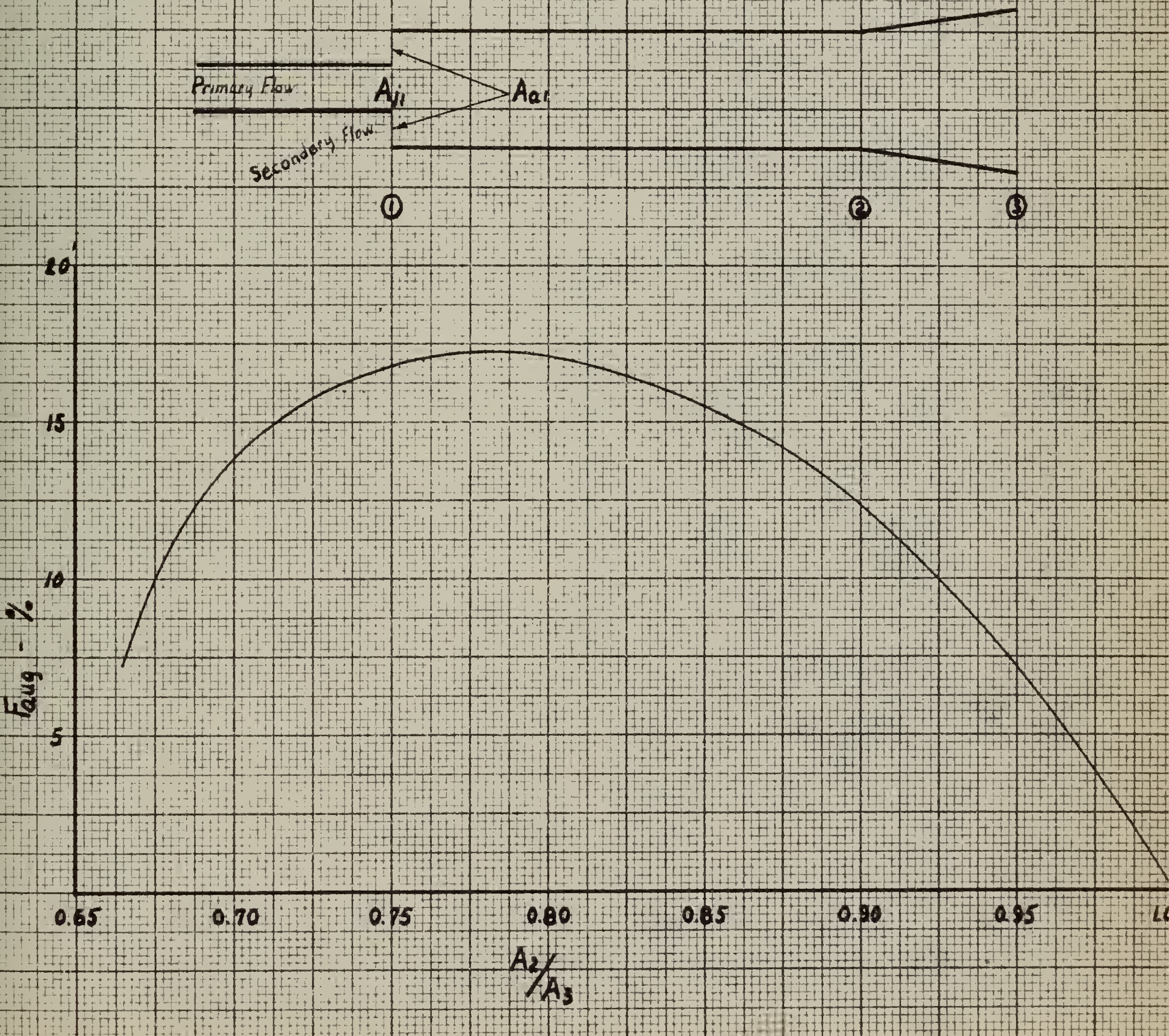

PRIMARY MASS FLOW
P₁/P₀
1.0
0.9
0.8
0.7
0.6
0.228
0.232
0.236
0.240
Wj - #/sec
SECONDARY MASS FLOW
P₁/P₀
0
0.1
0.2
0.3
0.4
Wa - #/sec
AREA RATIO
P₁/P₀
0.7
0.8
0.9
1.0
A₂/A₃
PRIMARY VELOCITY
P₁/P₀
800
900
1000
1100
1200
Vj₁ - ft/sec
SECONDARY VELOCITY
P₁/P₀
0
200
400
600
800
Va. - ft/sec
EXIT VELOCITY
P₁/P₀
400
500
600
700
800
V₃ - ft/sec

Fig 1

THRUST AUGMENTATION
VS
AREA RATIO

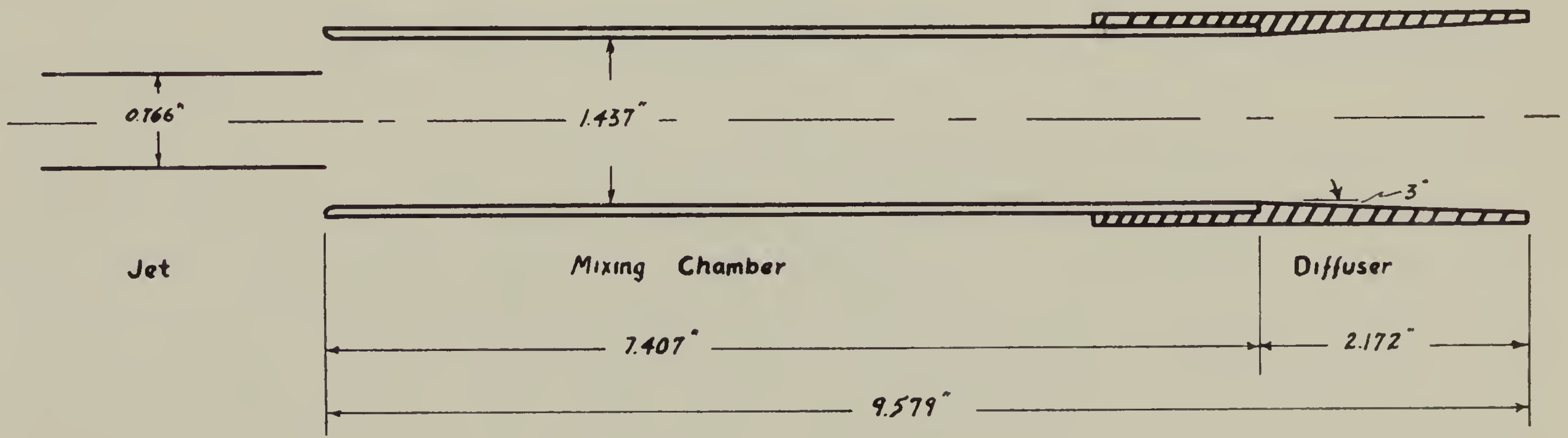
Fig. 2



JET AND AUGMENTOR

Scale: 1/15" = 1"

Fig. 3



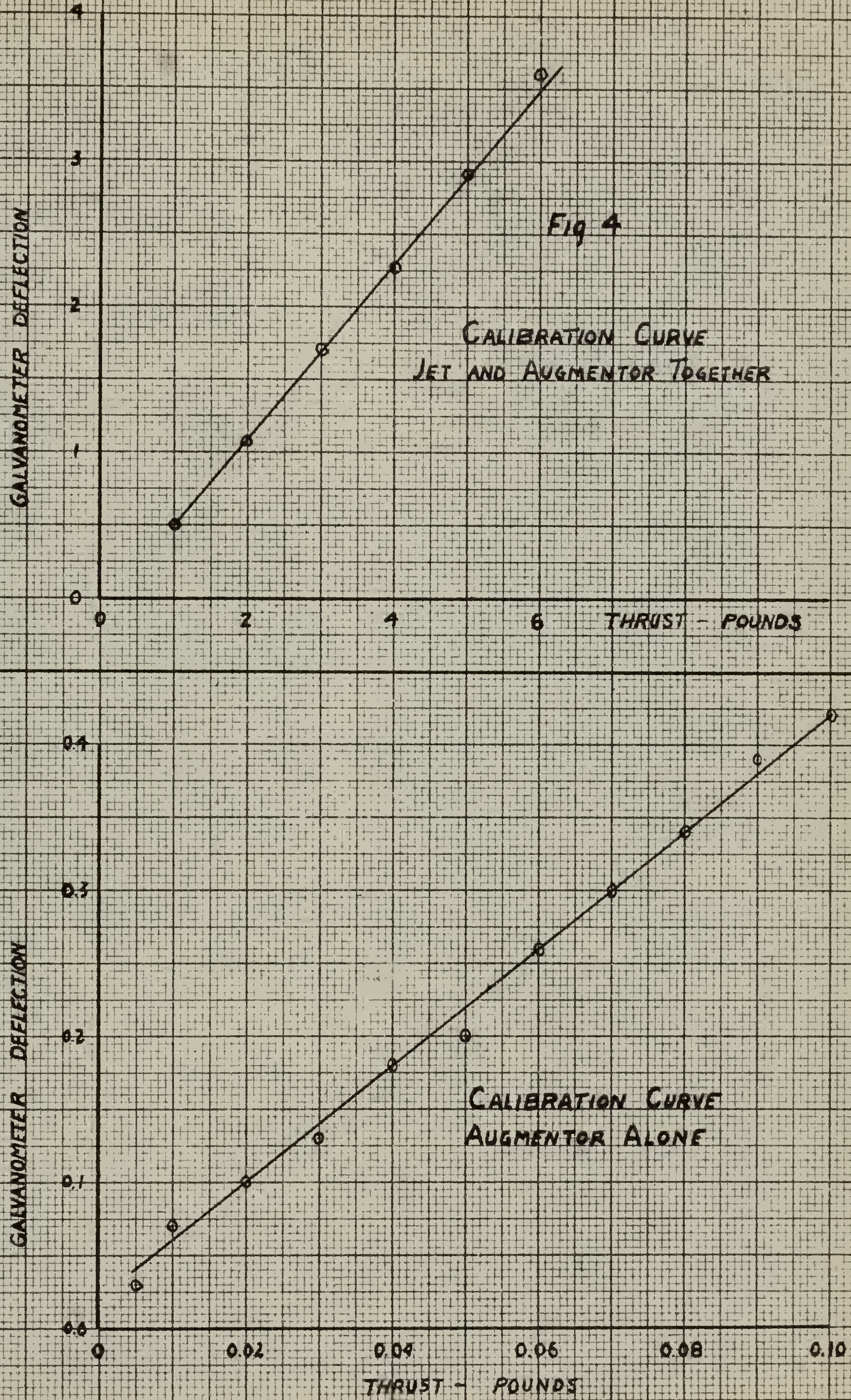


Fig 4

CALIBRATION CURVE
JET AND AUGMENTOR TOGETHER

CALIBRATION CURVE
AUGMENTOR ALONE

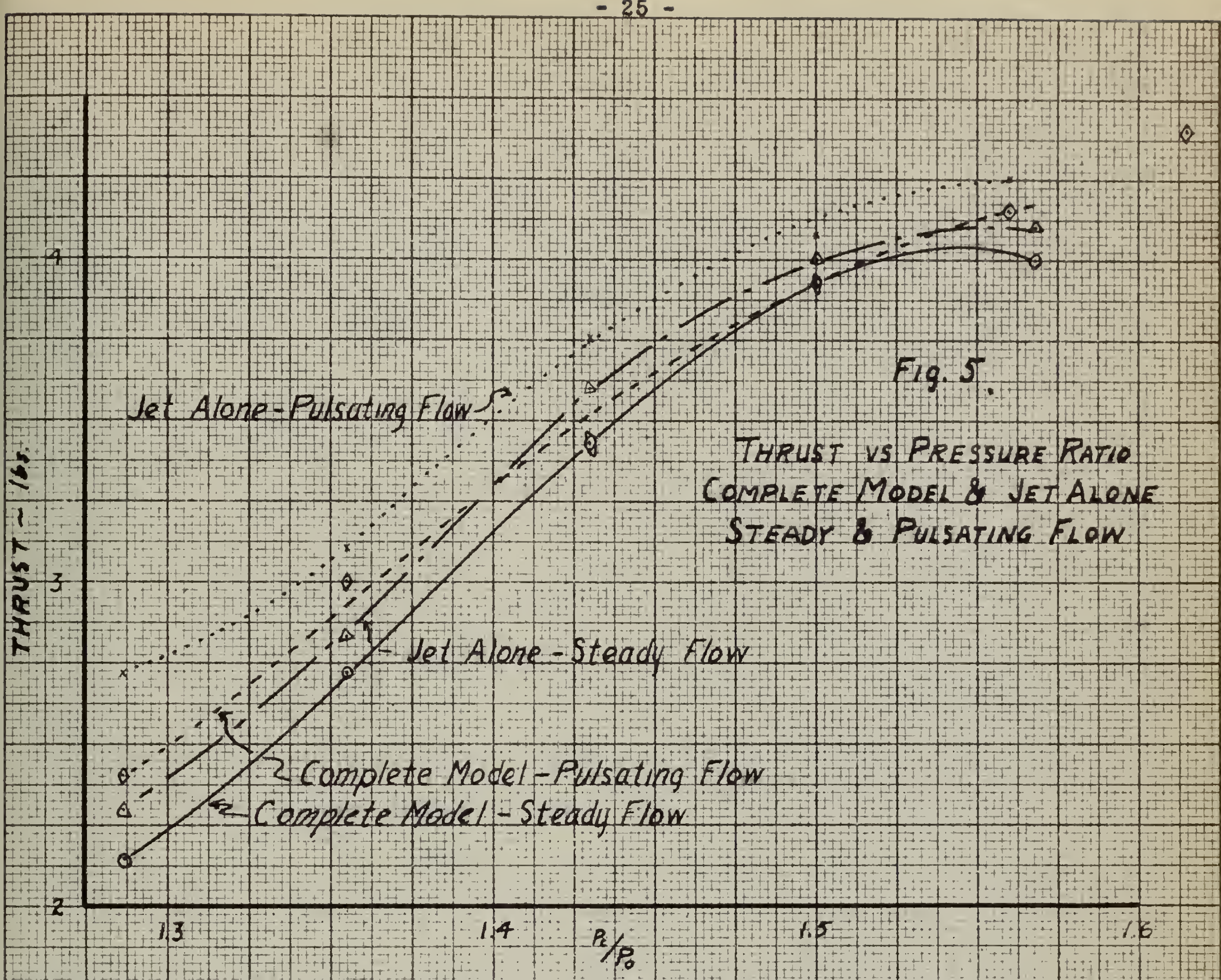
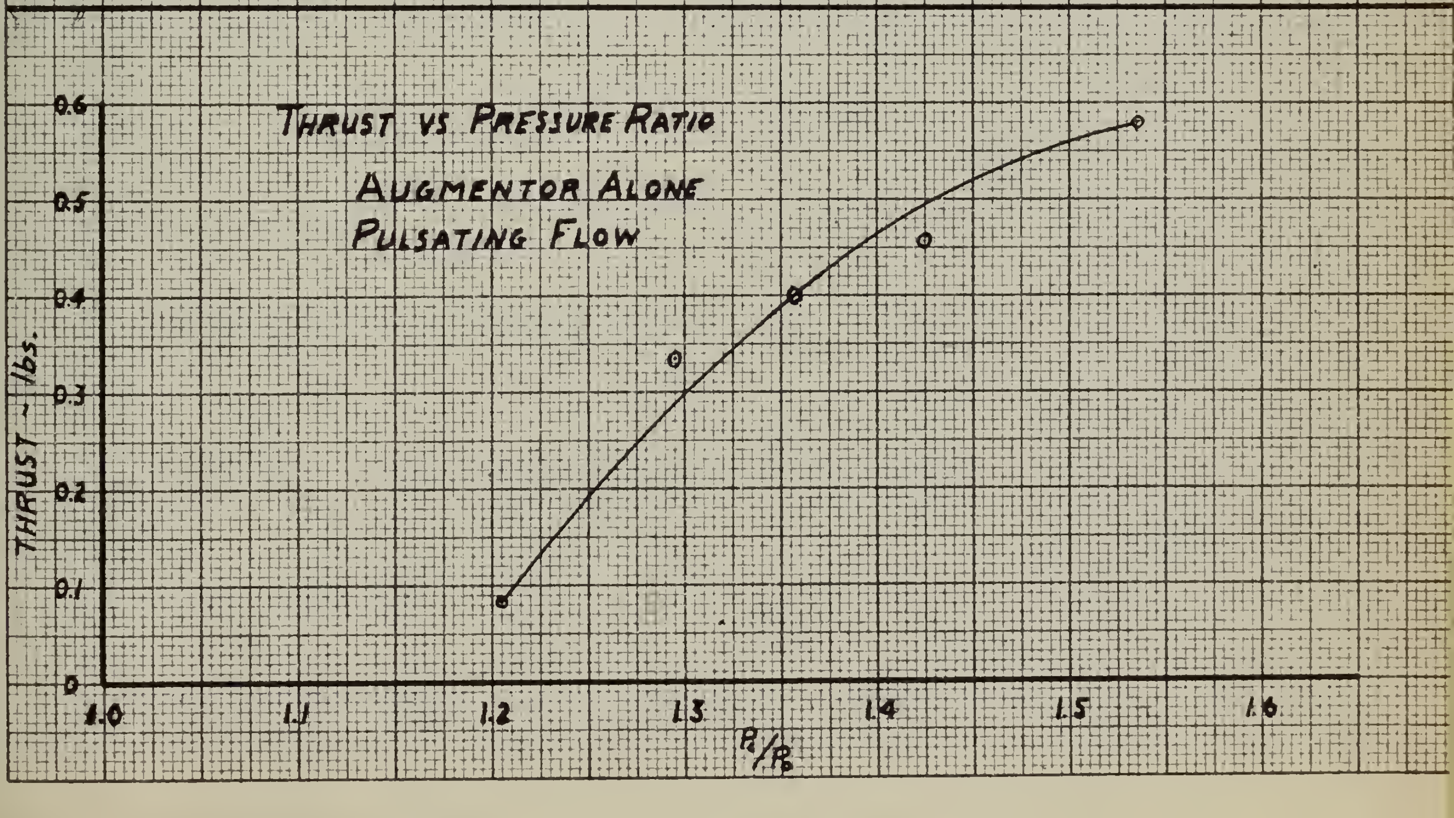


Fig. 5.

THRUST VS PRESSURE RATIO
COMPLETE MODEL & JET ALONE
STEADY & PULSATING FLOW



THRUST VS PRESSURE RATIO
AUGMENTOR ALONE
PULSATING FLOW

APPENDIX A

DESIGN OF AUGMENTOR

I. Derivation of Equations

To determine the optimum nozzle area of the duct, a plot of thrust augmentation against area ratio was made. The following equations were derived in the manner of Reference (f). See page 4 for definitions of the notation used. The following theoretical analysis neglects frictional losses and assumes mixing to be complete. The mixing chamber is designed for constant area. Compressibility is taken care of by the use of the thermodynamic General Energy relation, and the equations of Continuity, Momentum and State are all used. The following further assumptions are made:

$$T_o = T_c$$

$$p_3 = p_o$$

$$p_1 = p_2$$

From the General Energy Equation

$$V_{j_1}^2 - V_c^2 = 2gJC_p(T_o - T_1) \qquad (a)$$

Equation for Adiabatic expansion in the nozzle

$$\frac{T_1}{T_c} = \left(\frac{\rho_1}{\rho_c}\right)^{\gamma-1} = \left(\frac{p_1}{p_o}\right)^{\frac{\gamma-1}{\gamma}} \qquad (b)$$

Combining (a) and (b) we have for $V_c = 0$

$$V_{j_1} = \sqrt{2gJC_pT_c\left[1 - \left(\frac{p_1}{p_c}\right)^{\frac{\gamma-1}{\gamma}}\right]} \qquad (1)$$

From the equation of State and equation (b)

$$\rho_{j_1} = \rho_c\left(\frac{p_1}{p_c}\right)^{\frac{1}{\gamma}} = \frac{p_c}{gRT_c}\left(\frac{p_1}{p_c}\right)^{\frac{1}{\gamma}} \qquad (2)$$

Continuity equation

$$W_{j_1} = g\rho_1 V_j A_{j_1} \qquad (3)$$

Substituting in eqns (1), (2) and (3) gives

$$W_{j_1} = \frac{p_c}{RT_c}\left(\frac{p_1}{p_c}\right)^{\frac{1}{\gamma}}\sqrt{2gJC_pT_c\left[1 - \left(\frac{p_1}{p_c}\right)^{\frac{\gamma-1}{\gamma}}\right]}\,A_{j_1} \qquad (4)$$

Similarly

$$W_{a_1} = \frac{p_o}{RT_o}\left(\frac{p_1}{p_o}\right)^{\frac{1}{\gamma}}\sqrt{2gJC_pT_o\left[1 - \left(\frac{p_1}{p_o}\right)^{\frac{\gamma-1}{\gamma}}\right]}\,A_{a_1} \qquad (5)$$

$$V_a = \sqrt{2gJC_pT_o\left[1 - \left(\frac{p_1}{p_o}\right)^{\frac{\gamma-1}{\gamma}}\right]} \qquad (6)$$

The stagnation temperatures of the primary and secondary air at station (1)

$$T_{as} = \frac{V_o^2}{2gJC_p} + T_o \qquad (7)$$

$$T_{js} = \frac{V_o^2}{2gJC_p} + T_c \qquad (8)$$

However, considering the velocity in the combustion chamber equal to zero, and since the forward speed is also zero:

$$T_{as} = T_o \qquad (9)$$

$$T_{js} = T_c \qquad (10)$$

Assuming uniform temperature and velocity distribution, at Station 2,

$$T_{2s} = \frac{V_2^2}{2gJC_p} + T_2 \tag{11}$$

From the general energy equation

$$T_{2s} = \frac{(T_{as}\ r + T_{js})W_j}{(r + 1)\ W_j} = \frac{r\ T_{as} + T_{js}}{r + 1} \tag{12}$$

where

$$r = W_a/W_j$$

Equating (11) and (12)

$$T_{2s} = \frac{r\ T_{as} + T_{js}}{r + 1} = \frac{V_2^2}{wgJC_p} + T_2 \tag{13}$$

Multiplying through by $\frac{\gamma R}{\gamma - 1}$

$$\frac{\gamma R}{\gamma - 1} T_{2s} = \frac{\gamma R(r\ T_{as} + T_{js})}{(\gamma - 1)\quad(1 + r)} = \frac{\gamma R T_2}{(\gamma - 1)} + \frac{V_2^2}{2g} \tag{14}$$

From the momentum equation

$$\frac{W_j V_{j_1}}{g} + \frac{W_a V_{a_1}}{g} = \frac{(W_a + W_j)V_3}{g} + (p_3 - p_1)\ A_2$$

and

$$r\ V_a + V_j = (r + 1)\ V_2 + \frac{gA_2(p_2 - p_1)}{W_j} \tag{15}$$

Combining the equation of continuity and state

$$W_j(1 + r) = \rho_2 V_2 A_2 g \text{ and } \rho_2 g = \frac{p_2}{RT_2}$$

We have

$$W_j(1 + r) = \left(\frac{p_2}{RT_2}\right) V_2 A_2 \text{ and } A_2 = \frac{W_j(1 + r)RT_2}{p_2 V_2} \tag{16}$$

Substituting equation (16) in equation (15) for A_2

$$\frac{(p_2 - p_1)\ (1 + r)gRT_2}{p_2V_2} = r\ V_a + V_j - (r + 1)V_2 \qquad (17)$$

From equation (14) we have

$$gRT_2 = \frac{\gamma-1}{\gamma}\left[g\left(\frac{\gamma R}{\gamma-1}\right)T_{2s} - \frac{V_2^2}{2}\right] = gRT_{2s} - \left(\frac{\gamma-1}{\gamma}\right)\frac{V_2^2}{2} \qquad (18)$$

Substituting (18) in (17)

$$\frac{(p_2 - p_1)\ (1 + r)\ \left[gRT_{2s} - \left(\frac{\gamma-1}{\gamma}\right)\frac{V_2^2}{2}\right]}{p_2V_2} = rV_a + V_j - (r + 1)V_2$$

and

$$\frac{(p_2 - p_1)\ \left[gRT_{2s} - \left(\frac{\gamma-1}{\gamma}\right)\frac{V_2^2}{2}\right]}{p_2V_2} = \frac{r\ V_a + V_j}{1 + r} - V_2$$

Letting

$$\frac{r\ V_a + V_j}{1 + r} = B \qquad (18a)$$

then

$$\frac{p_2 - p_1}{p_2}\ gRT_{2s} - \left(\frac{p_2 - p_1}{p_2}\right)\left(\frac{\gamma-1}{\gamma}\right)\frac{V_2^2}{2} = BV_2 - V_2^2$$

or rearranging

$$\left[1 - \left(\frac{p_2 - p_1}{p_2}\right)\left(\frac{\gamma-1}{2\gamma}\right)\right]V_2^2 - BV_2 + \left(\frac{p_2 - p_1}{p_2}\right)\ gRT_{2s} = 0$$

Using the quadratic formula for solution

$$V_2 = \frac{B + \sqrt{B^2 - 4\left[1 - \left(\frac{p_2 - p_1}{p_2}\right)\left(\frac{\gamma-1}{2\gamma}\right)\right]\left[\left(\frac{p_2 - p_1}{p_2}\right)gRT_{2s}\right]}}{2\left[1 - \left(\frac{p_2 - p_1}{p_2}\right)\left(\frac{\gamma-1}{2\gamma}\right)\right]} \qquad (19)$$

For the case of $p_2 = p_1$, this reduces to

$$V_2 = B \tag{19a}$$

The exit velocity is calculated from

$$V_3 = \sqrt{V_2^2 + 2gJC_pT_2\left[1 - \left(\frac{p_3}{p_2}\right)^{\frac{\gamma-1}{\gamma}}\right]} \qquad \text{where } p_3 = p_o \tag{20}$$

The per cent thrust increase due to the augmentor is

$$F_{aug} = \left[\frac{(W_a + W_j)\,V_3 - W_jV_j}{W_jV_j}\right] 100 \tag{21}$$

To design the augmentor, it is necessary to know the areas of the various cross sections that will give the assumed value of p_1/p_o. A_j and A_a are known since they were chosen arbitrarily.

$$A_2 = \frac{(1 + r)W_jgRT_2}{V_2p_2g} = \frac{(1 + r)W_jRT_2}{V_2p_2} \tag{22}$$

which merely indicates that mixing is complete at station 2, since by rewriting we have

$$r = \frac{A_2V_2p_2}{W_jRT_2} - 1 \qquad \text{or } W_a + W_j = W_2$$

$$A_3 = \left[\frac{(1 + r)\,W_jR}{V_3p_o}\right]\left[T_2\left(\frac{p_3}{p_2}\right)^{\frac{\gamma-1}{\gamma}}\right] = \left[\frac{(1 + r)W_jR}{p_oV_3}\right]\left[T_2\left(\frac{p_o}{p_1}\right)^{\frac{\gamma-1}{\gamma}}\right] \tag{23}$$

Dividing equation (22) by (23)

$$\frac{A_2}{A_3} = \frac{V_3\,p_o}{V_2\,p_1}\left(\frac{p_1}{p_o}\right)^{\frac{\gamma-1}{\gamma}} \tag{24}$$

II. Dimensions of the Augmentor

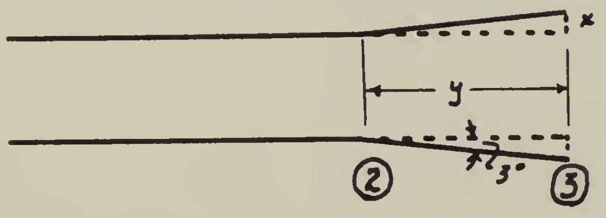
a. Mixing Chamber

The mixing chamber should be four (4) or five (5) diameters in length in accordance with reference (e), in order to have complete mixing. With d_1 (the diameter at station 1) having been selected as 1.437", and using a length of five (5) diameters, the length of the mixing chamber is equal to

$$1.437 \times 5 = 7.185".$$

b. Diffuser Section

Limiting the angle of expansion to three (3) degrees, and using an optimum area ratio of 0.75 obtained from Figure 2, we have



$$\frac{A_2}{A_3} = \frac{4\pi D_2^2}{4\pi D_3^2} = 0.75$$

or $D_3 = 1.66"$

$$x = \frac{1.66 - 1.437}{2} = 0.1115''$$

since $\tan 3^\circ = x/y$

$y = 0.1115/0.05241 = 2.13''$

= length of diffuser

c. Final dimensions

$D_1 = 1.437''$

$D_2 = 1.660''$

$L = 7.185 + 2.13 = 9.315''$

APPENDIX B

DESIGN OF PULSATOR

I. Resonant Frequency of Augmentor

Free vibrations are those having a frequency entirely determined by the constants and properties of the vibrating body itself. Forced vibrations result when the body is set in motion by periodic impulses caused by outside forces. Resonance occurs when the frequency of the forced vibrations is the same as the natural frequency of the body itself, and results in the free vibrations reinforcing the forced vibrations.

From reference (k), the equation for vibrations of an air column is

$$f = \frac{V}{\lambda} = \frac{nV}{2l}$$

where

V = velocity of sound

n = number of loops formed by the vibrations

= 1, 2, 3 etc for open end tubes and

= 1/2, 3/2, 5/2 etc for closed tubes

l = corrected length

The correction for the length is necessary since the re-

flection doesn't occur exactly in the plane of the open end, but somewhat beyond it. Assuming that the augmentor is an open cylinder, the plane of the reflection is considered to be outside the tube a distance 0.6 times the radius of the tube. Thus, the corrected length is

$$l = 9.579 \quad 2 \times 1.437 = 11.302''$$

$$V = \sqrt{\gamma RT} = \sqrt{(1.4)\,(1715)\,(474.4)} = 1067 \text{ ft/sec}$$

With $n = 1$

The resonant frequency becomes

$$f = \frac{nV}{2l} = \frac{(1067)\,(12)}{(2)\,(11.302)} = 566 \text{ vibrations/sec}$$

II. Design

To convert the steady flow source of air into a pulsating flow, the pulsating device in Figure 6 was built. The disc was belt driven by a motor connected to a pulley mounted on the disc shaft.

Since the resonant frequency of 566 vibrations per second required 33960 rpm from any source of power, the rotating disc was designed with ten holes in order to cut the required rpm down to 3396. The holes were spaced a "hole" apart such that the supply of air was cut off the same amount of time that it was free to flow.

An attempt was made to build the pulsating device with a 0.005 clearance between the disc and its housing, but lack of proper equipment made it necessary to weld the housing sides together. This resulted in a certain amount of warpage, and many many hours of work to smooth up the assembly such that the disc would turn freely. It was finally necessary to cut through the housing on one side and mount a ball bearing such that the bearing extended inside the housing a distance of 0.005 and provided a rolling surface for the disc. Thus, when the disc was under a side pressure exerted by the air flowing through the pulsator, any side movement of the disc was contained by the bearing, and the disc no longer rubbed against the side of the housing. This arrangement allowed satisfactory results in obtaining a pulsating flow.

In order to operate at exact resonant frequency rather than an approximate one, it was planned to use a variable speed motor such that the frequency could be easily varied. However, this was not possible at the time due to the lack of a suitable power source.

The problem of providing a satisfactory pulsating flow developed into a major one.

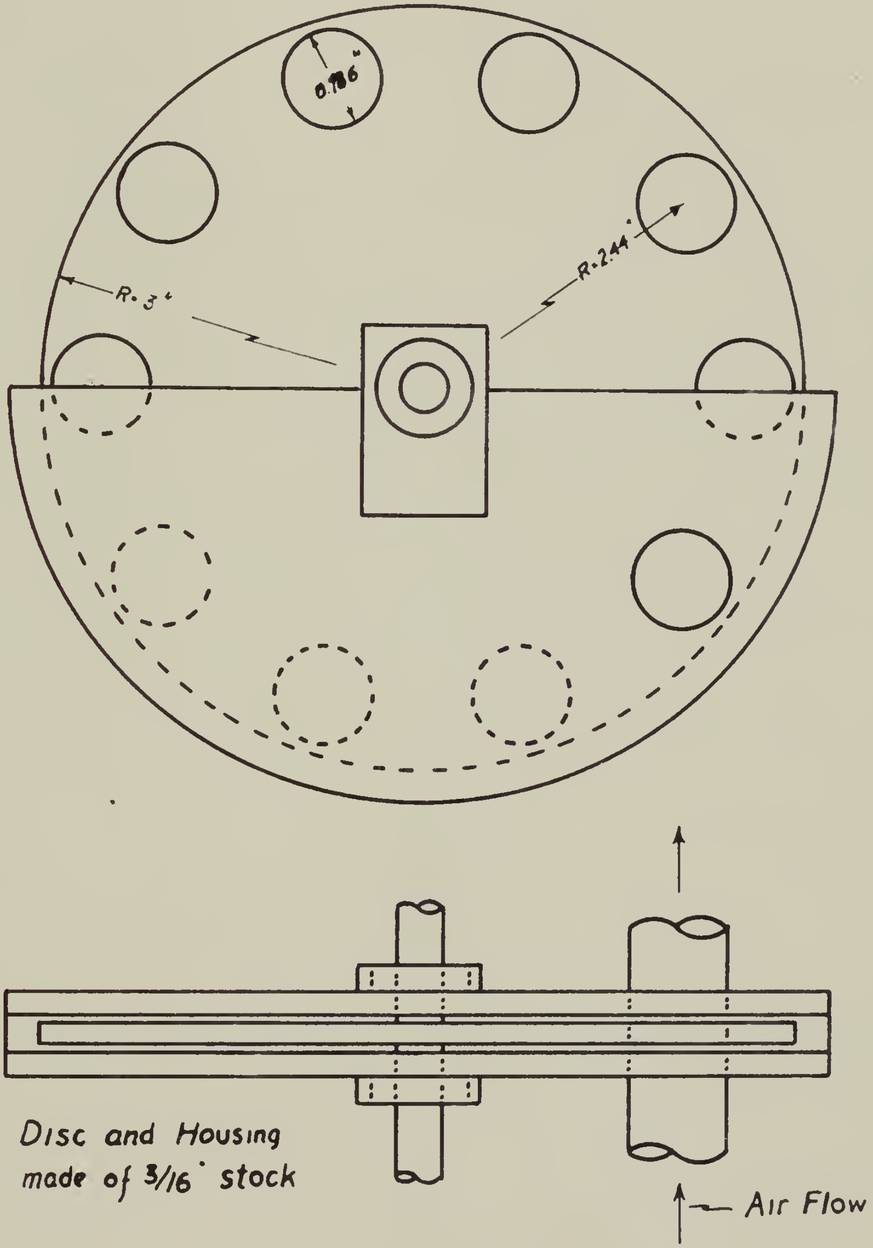
Should any more work be done along these lines, it is recommended that the pulsator be rebuilt, and the housing milled

from solid stock to avoid warpage. It is further suggested that roller bearings be used in place of the ball bearings. Although the side play tolerance of the ball bearing was only 0.003", this was enough to allow the disc to rub against the sides when loaded by the air pressure. These two changes should make a pulsator capable of operating at any reasonable pressure ratio, and driven by a variable speed motor, would allow operation at any pulsating frequency.

PULSATING DEVICE

Scale: 1/15" = 1"

Fig. 6



Disc and Housing made of 3/16" stock

DATE DUE

OC 28 62
6 AUG 71

11485
S 10482

Thesis
S76

13197

Stone

A comparison of the jet augmentation resulting from steady and pulsating primar
flow.

OC 28 62

11485

.97
ent-
sa-

thesS76
A comparison of the jet augmentation res
3 2768 002 02041 4
DUDLEY KNOX LIBRARY